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AND THE WORLD TURNED SPIN TESTING.THE DG-1000S

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AIR FORCE TEST CENTER
EDWARDS AFB, CA

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14. ABSTRACT

During the past 10 years, the Society of Experimental Test Pilots (SETP) has published over 250 new technical papers in its online database. Of these, only four of them – less than 2% -- directly address the topic of spin testing. Since it apparently is not a test discipline many of us encounter, it might seem logical to question the importance of remaining knowledgeable of its precepts. A survey of the lessons-learned from the SETP spin papers that *are* available – when compared to the lessons-learned of this project – reveals a striking recurrence of themes. Seemingly minor aberrations in the aircraft mold line, for example – particularly on or near the nose of the aircraft or wing leading edge – have led to the discovery of unpredicted out-of-control behaviors and potentially-dangerous recoverability characteristics. In the face of such uncertainties, selecting an effective build-up approach has proven problematic in some cases. One of the goals of this paper, then, is to refresh understandings that could be needed on a moment's notice. It examines spin behaviors which were previously undocumented and unusual, identifies unexpected hazards, offers techniques to mitigate them, and proposes a new method of assigning spin mode modifiers for highly/violently oscillatory spins. Finally, it is hoped it will serve as a readily-available primer on the topic of spin testing, while helping to banish certain preconceived ideas and attitudes which consistently prove self-critiquing in the flight test profession. On occasion, they even prove fatal.

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AND THE WORLD TURNED: SPIN TESTING THE DG-1000S

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Presented to
The Society of Experimental Test Pilots
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Figure 1. Spin Testing over Roger's Dry Lake, Edwards AFB, CA.

INTRODUCTION: RESPECTING THE DISCIPLINE

During the past 10 years, the Society of Experimental Test Pilots (SETP) has published over 250 new technical papers in its online database. Of these, only four of them – less than 2% -- directly address the topic of spin testing. Since it apparently is not a test discipline many of us encounter, it might seem logical to question the importance of remaining knowledgeable of its precepts. If you did question its importance, recent experience suggests you would not be alone: experienced SETP members have even gone so far as to openly question whether or not the USAF Test Pilot School (TPS) should continue training its students on the topic.

A survey of the lessons-learned from the SETP spin papers that *are* available – when compared to the lessons-learned of this project – reveals a striking recurrence of themes. Seemingly minor aberrations in the aircraft mold line, for example – particularly on or near the nose of the aircraft or wing leading edge – have led to the discovery

of unpredicted out-of-control behaviors and potentially-dangerous recoverability characteristics.[1] In the face of such uncertainties, selecting an effective build-up approach has proven problematic in some cases.[2]

Even when not engaged in stall, departure susceptibility and/or spin testing, test pilots routinely perform maneuvers that have led to sudden and unpredicted departures from controlled flight. Stability and control testing with large lateral asymmetries opens the door to such a possibility, for example.[3] SETP members have recently listened to presentations describing unexpected departures during seemingly benign maneuvers: the unintended inverted spin experienced by the *SpaceShipTwo* test crew – immediately following release from *WhiteKnightTwo* – provides a compelling example.[4]

One of the goals of this paper, then, is to refresh understandings that could be needed on a moment's notice. It examines spin behaviors which were previously undocumented and unusual, identifies unexpected hazards, offers techniques to mitigate them, and proposes a new method of assigning spin mode modifiers for highly/violently oscillatory spins. It also informs the reader of what recent USAF TPS graduates know – and by inference, don't know – about this field of testing, where such insight is prerequisite to effective risk mitigation. Finally, it is hoped it will serve as a readily-available primer on the topic of spin testing, while helping to banish certain preconceived ideas and attitudes which consistently prove self-critiquing in the flight test profession. On occasion, they even prove fatal.

UNDERSTANDING THE USER REQUIREMENT

As part of its mission to graduate full-spectrum test professionals, TPS has used the ASK-21 sailplane to conduct spin test training for over 20 years: over 1000 testers have been trained in this aircraft to date. First spin-tested for the USAF by Charles Precourt (F) in 1989[5], the ASK that is available to TPS is approaching the end of its useful lifespan. The TPS Flying Qualities Branch required a replacement aircraft that would facilitate an overall learning objective to "practice making accurate observations in a highly dynamic flight environment" – as well as several specific learning objectives. These included: 1) Using Phase A-D stalls to determine the aircraft's MIL-F-83691B susceptibility to departure, 2) Identifying MIL-F-83691B spin phase boundaries, 3) Identifying MIL-F-83691B Spin Mode Modifiers, 4) Investigating the efficacy of various spin recovery procedures and 5) Investigating control effects while in the spin. The Flying Qualities Branch also wanted to investigate the feasibility of further-developing students' observational skills by exposing them to inverted spin testing.

The Precourt spin test was performed in the wake of a fatal ASK-21 stall/spin mishap at the U.S. Air Force Academy. Testing revealed numerous characteristics that were not described in the published flight manual. Since that time, the USAF has elected to independently spin-test certified sailplanes prior to using them in their training curricula. In light of TPS' intentions to employ test training maneuvers that would not necessarily have been performed during initial certification testing, such an evaluation seemed especially pertinent.

While MIL-F-83691B was formally cancelled "without replacement"[6] in 1996, no substantive means of characterizing departure susceptibility or spin mode behavior has risen to take its place. TPS has elected to continue teaching its conventions and test procedures. Per its language, a departure "may be characterized by a divergent, large amplitude, un-commanded aircraft motion." What constitutes "large amplitude" appears to be left to sound engineering judgement: for test training, the test team declared a departure event at the moment any of the following parameters were exceeded: 1) 30 degrees of pitch 2) 60 degrees of roll, or 3) 90 degrees of heading change. It is important to note that measurement of these post-stall excursions began immediately after any aggravating control input was neutralized. The test team also defined "divergent" to mean that pitch, roll or yaw angles were continuing to change at a steady or increasing rate when these criteria were exceeded. See Table 1 for adapted MIL-F-83691B Phase A-D Stall descriptions and departure susceptibility ratings. Maneuvers were adapted to accommodate the absence of an Angle of Attack (AoA) display in the DG-1000S cockpit: indicated airspeed bleed rates – not AoA rates – were used. To emulate the MILSTD's defined "smooth" and "abrupt" AoA-rate test procedures, 1 kt/sec and 5 kt/sec airspeed bleed rates were used, respectively. The 5 kt/sec entry was

Stalls	Maneuver Description and Departure Susceptibility Rating
Phase A	<u>**Hold specified airspeed bleed rate until**</u>: **a)** Definite g-break, or **b)** a rapid, un-commanded angular motion, or **c)** the aft stick stop has been reached and no other indication of stall has occurred, or **d)** sustained intolerable buffet. If a departure occurs during a Phase A stall, the aircraft is rated **"extremely susceptible"** to departure.
Phase B/C	Phase A stall with one/three second(s) aggravating rudder, respectively. If a departure *first* occurs during a Phase B stall, the aircraft is rated **"susceptible"** to departure. If a departure *first* occurs during a Phase C stall, the aircraft is rated **"resistant"** to departure. If the aircraft does not depart during any Phase A-C stall, it is rated **"extremely resistant"** to departure.
Phase D	Deliberate spin attempt.

Table 1. MIL-F-83691B Phase A-D Stall Definitions

Spin Phase	Definition
"Incipient"	The initial, transitory phase of the motion during which it is not possible to identify the spin mode.
"Developed"	The phase of the spin during which it is possible to identify the spin mode.
"Fully Developed"	Attained when the trajectory has become vertical and no significant change is noted in the spin characteristics from turn to turn.

Table 2. MIL-F-83691B Spin Phase Definitions

Sense	Oscillations	Attitude		Rate	
The sign of AOA (derived from pitch attitude). Positive or negative AOA indicates an upright or inverted spin, respectively.	The qualitative magnitude of three-axis oscillations, rated by pilot comments as: - **"Smooth"** - **"Mildly Oscillatory"** - **"Oscillatory"** - **"Highly oscillatory"** - **"Violently Oscillatory"**	The magnitude of the average AOA (α_{avg}), further rated as follows:		The body-axis yaw rate (R), further rated as follows:	
		"Extremely Steep"	Stall $\alpha_{avg} < \alpha_{avg} <35$ deg	**"Slow"**	R ≤ 60 deg/sec
		"Steep"	35 deg ≤ α_{avg} < 70 deg	**"Fast"**	60 deg/sec < R ≤ 120 deg/sec
		"Flat"	α_{avg} ≥ 70 deg	**"Extremely Rapid"**	R ≥ 120 deg/sec

Table 3. MIL-F-83691B Spin Mode Modifiers

also selected to allow us to evaluate the impact of student error when attempting to set a 1 kt/sec bleed rate, as well as verify that the 1 kt/sec entry produced the most repeatable test results. Table 2 provides a review of MIL-F-83691B spin phase definitions: it is important to note the "turn to turn" qualifier for the fully-developed phase. Table 3 provides a review of MIL-F-83691B ratings for spin mode modifiers: again, with no AoA display available in most sailplane cockpits, TPS students have been trained to visually estimate α_{avg} using pitch attitude. Under this scheme, < 20 degrees of nose-down pitch is rated as "flat," where > 55 degrees of nose-down pitch is rated as "extremely steep." Intermediate pitch angles are rated "steep."

TRANSLATING REQUIREMENTS INTO A TEST

See Figures 2 and 3. The Glaser-Dirks DG-1000S presented itself as a promising candidate replacement aircraft for the ASK-21, largely due to its unique tail and cockpit ballasting system. This system permits some degree of control over aircraft center-of-gravity (CG) and pitch moment of inertia (I_{yy}), independent of aircrew weight. This suggested the potential for repeatable spin behaviors and recovery characteristics during test training.

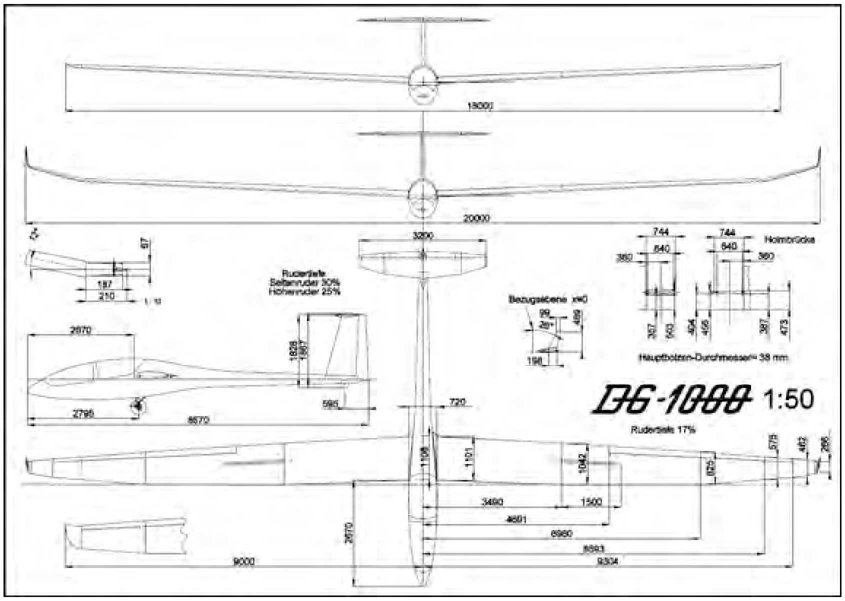

Figure 2. DG-1000 Dimensions

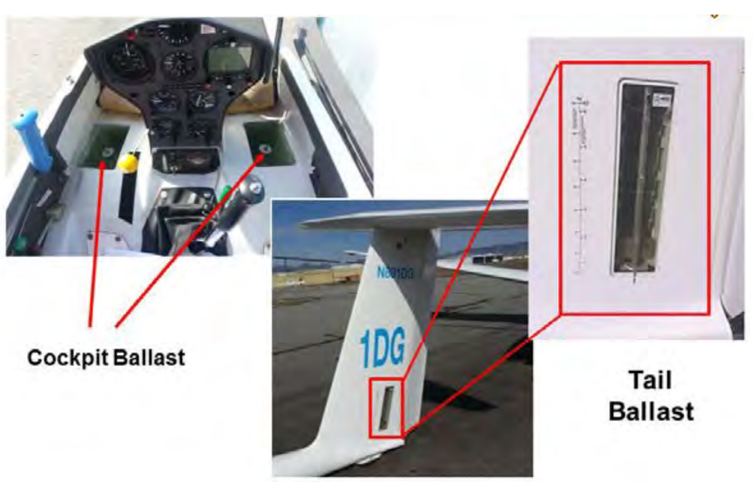

Figure 3. DG-1000S Ballast Compartments

The DG-1000S is a two-place, tandem, high performance sailplane that can be configured with an 18-meter or 20-meter wingspan. Best L/D in the 20-m configuration is 46:1. It features a mid-mounted wing, T-tail, conventional reversible flight controls, and spoilers. The undercarriage consists of a high spring-mounted electrically-retractable main wheel with disc brake and a tail wheel. The wing is constructed from carbon-fiber reinforced plastic, while the fuselage was mainly glass-fiber reinforced plastic, with steel as necessary for the landing gear. Load factor limits are +7/-5g. Manufactured in Germany, the DG-1000S is certified under the airworthiness requirements of the *Joint Aviation Authorities,* (JAR) *Joint Requirements JAR-22 Sailplanes and Power Sailplanes* for spins in the Utility category for both wing configurations; however, inverted spins are certified only in the 18m configuration.

TPS learning objectives translated readily into specific test objectives: the test team aimed to evaluate how well – and safely – the aircraft illustrated those characteristics TPS students needed to observe and assess. The test team also anticipated the need to evaluate the impact of student control input errors on upright spin recovery characteristics – henceforth referred to as a “misapplied controls” investigation. This investigation was not deemed necessary for inverted spin testing, as inverted spins were anticipated to be an instructor demonstration during a curriculum event. Training requirements did not mandate an evaluation of accelerated stall/spin entries.

Once test objectives had been appropriately narrowed to meet these requirements, identifying data requirements for the test was relatively straightforward. Since the focus of the training event was developing student observational skills in a spin, test pilot observations constituted the primary data source. To remain legally certified, no permanent modifications to the (privately owned) aircraft were permitted: this prohibited us from installing the necessary instrumentation to precisely measure parameters like AoA, Angle of Sideslip, airspeed, or altitude. Moreover, defined test training requirements did not explicitly require this data. See Figure 4. Lacking a cockpit ADI, markers were placed on the canopy to help visually identify 20 degrees and 55 degrees of nose-down pitch – to facilitate identification of the “attitude” spin mode modifier. A yaw string provided the pilot an approximation of sideslip as well as AoA trend information.

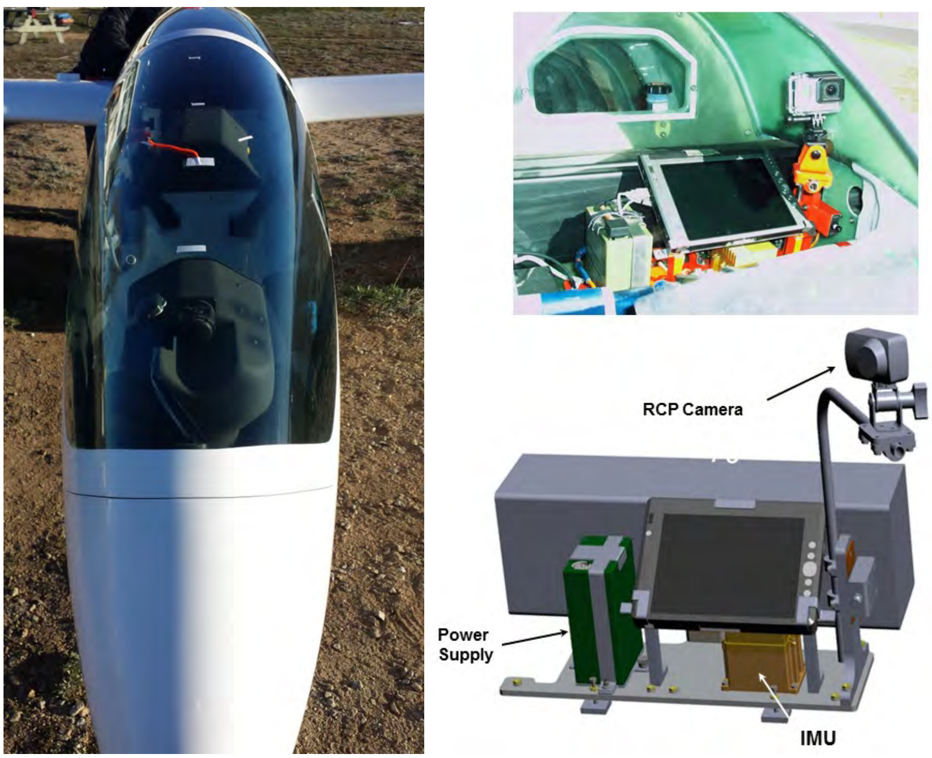

Figure 4. DG-1000S Canopy Markers and Instrumentation System

Thanks to the proliferation microelectromechanical systems (MEMS) technology, the test instrumentation team was able to supplement pilot observations with a compact, lightweight instrumentation system affixed to a bulkhead immediately behind the rear cockpit. The pallet included a MEMSIC NAV-440 inertial measurement unit (IMU) which was capable of measuring body-axis pitch, roll and yaw angles, derived body-axis angular-rates, inertial velocity and load factor. An internal attitude-heading-reference-system (AHRS) also provided aircraft heading and heading-rate information using a 3-axis internal magnetometer.[7] IMU control and data recording was handled via tablet PC. Front and rear digital cameras also captured cockpit instrument readings and out-the-window heading and attitude references for post-flight review.

REVIEWING THE THEORY; SPEAKING THE LANGUAGE

See Figure 5. In a spin, both wings are generally beyond stall angle of attack, but one wing is at a higher AoA than the other. This more completely-stalled wing experiences less lift and greater induced drag – causing it to "retreat." The other wing simultaneously experiences more lift and less drag, causing it to "advance." This is the aerodynamic forcing function for autorotation.

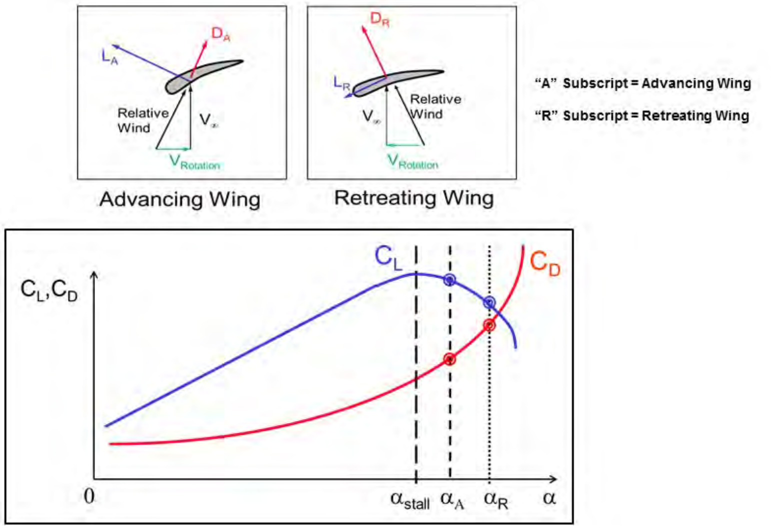

Figure 5. Spin Aerodynamics

See Figure 6. An aircraft with positive static stability experiences an aerodynamic nose-down pitching moment in a spin, as depicted on the left of the figure. Mass distribution along the length of the fuselage – coupled with centripetal acceleration (depicted on the right) tends to pitch the nose back up. Shortly after a departure, these forces are often not in balance with each other, leading to incipient-phase oscillations in pitch, roll and yaw. In a fully-developed spin, aerodynamic forces are balanced against equally-opposing inertial forces, producing essentially constant spin parameters "turn to turn."

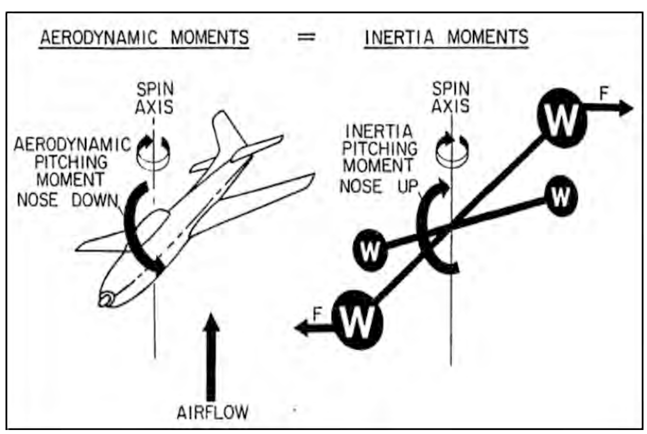

Figure 6. The Balance of Aerodynamic and Inertial Forces in a Spin

The interaction between aerodynamic and inertial forces can also be understood via review of aircraft equations of motion. X_b, Y_b, and Z_b refer to the orthogonal body axis frame of reference, centered on the aircraft CG. See Figure 7: specific orientation of this axis system will be addressed shortly. *P, Q,* and *R* refer to body-axis roll, pitch and yaw rates, respectively. *L, M* and *N* refer to body-axis roll, pitch and yaw moments, respectively. $\vec{H}$ refers to total angular momentum, where $\vec{M}$ refers to total moment – both about the CG. $\vec{I}$ represents inertia about a

specific body axis (I_{xx}, I_{yy}, I_{zz}) or a product of inertia between two specific body-axes (I_{xz}, for example). Recall the moments of inertia describe an aircraft's resistance to rotation about its respective axis, where products of inertia describe how a moment applied to one axis changes angular momentum in another. Products of inertia, then, provide a measure of the asymmetry of mass distribution on either side of a body-axis plane. $\vec{\omega}$ represents angular velocity.

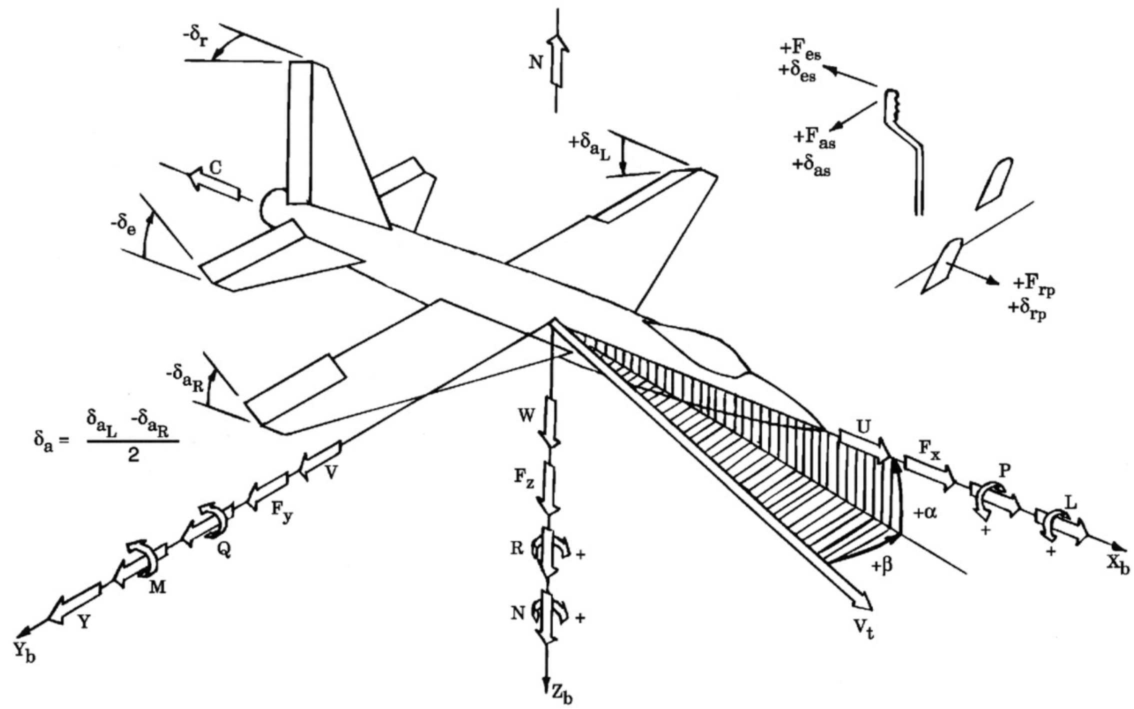

Figure 7. Body-Axis Definitions and Sign Conventions

Derived equations of motion for a spin rest upon several important assumptions:

1. *An inertial reference frame is used.*
2. *The aircraft can be treated as a rigid body in translation and rotation.*
3. *The mass of the aircraft remains constant during the maneuver.*
4. *A flat, non-rotating Earth is a suitable inertial reference frame.*
5. *Aircraft motion will be described using a body-fixed reference frame.*
6. *The atmosphere is at rest relative to the inertial reference frame.*
7. *Thrust effects are negligible for a sailplane.*
8. *The aircraft has symmetry about the XZ plane. Therefore, Iyz = Ixy = 0.*

From Newton's Second Law, the sum of applied forces equals the time-rate-of-change of linear momentum. The rotational equivalent of this concept for spins is similar: the sum of applied aerodynamic moments equals the time-rate-of-change of angular momentum, or:

$$\left[\frac{d\vec{H}}{dt}\right]_{Inertial} = \sum(\vec{M}_{aero})$$

Where,

$$\vec{H} = \vec{I}\vec{\omega}$$

Therefore,

$$H_{Inertial} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \begin{bmatrix} P \\ Q \\ R \end{bmatrix}$$

With I_{yz} and I_{xy} = 0, (assumption #8) four terms are dropped from the inertia tensor above. The balance between aerodynamic moments and time-rate-of-change of angular momentum then becomes:

$$\begin{aligned} \dot{P}I_{xx} + QR(I_{zz} - I_{yy}) - (\dot{R} + PQ)I_{xz} &= L_{aero} \\ \dot{Q}I_{yy} - PR(I_{zz} - I_{xx}) + (P^2 - R^2)I_{xz} &= M_{aero} \\ \dot{R}I_{zz} + PQ(I_{yy} - I_{xx}) + (QR - \dot{P})I_{zx} &= N_{aero} \end{aligned}$$

Solving these for angular acceleration in each axis gives us:

$$\dot{P} = \frac{I_{yy} - I_{zz}}{I_{xx}} QR + \frac{I_{xz}}{I_{xx}}\left(\dot{R} + PQ\right) + \frac{L_{aero}}{I_{xx}}$$

$$\dot{Q} = \frac{I_{zz} - I_{xx}}{I_{yy}} PR - \frac{I_{xz}}{I_{yy}}\left(P^2 - R^2\right) + \frac{M_{aero}}{I_{yy}}$$

$$\dot{R} = \frac{I_{xx} - I_{yy}}{I_{zz}} PQ + \frac{I_{xz}}{I_{zz}}\left(\dot{P} - QR\right) + \frac{N_{aero}}{I_{zz}}$$

We will now orient the body axis so that it aligns with the inertial axis – by assuming an X-Y plane of symmetry. This leads to our final assumption:

9. The aircraft body axis system is chosen to coincide with the aircraft inertial axis. Therefore, Ixz=0.

In most sailplanes, the vertical tail accounts for the most obvious – and relatively minor – asymmetry across the X-Y plane. This final assumption will cancel all products of inertia. While approximate, this is close enough to the truth to illuminate important characteristics. The equations now reduce to:

$$\dot{P} = \frac{I_{yy} - I_{zz}}{I_{xx}} QR + \frac{L_{aero}}{I_{xx}}$$

$$\dot{Q} = \frac{I_{zz} - I_{xx}}{I_{yy}} PR + \frac{M_{aero}}{I_{yy}}$$

$$\dot{R} = \frac{I_{xx} - I_{yy}}{I_{zz}} PQ + \frac{N_{aero}}{I_{zz}}$$

For a wing-loaded aircraft like the DG-1000S, $I_{xx} > I_{yy}$. Also recall that Izz is the largest inertia term. Therefore, the sign of the inertial terms are as shown:

$$\dot{P} = \overset{(-)}{\frac{I_{yy} - I_{zz}}{I_{xx}}} QR + \frac{L_{aero}}{I_{xx}}$$

$$\dot{Q} = \overset{(+)}{\frac{I_{zz} - I_{xx}}{I_{yy}}} PR + \frac{M_{aero}}{I_{yy}}$$

$$\dot{R} = \overset{(+)}{\frac{I_{xx} - I_{yy}}{I_{zz}}} PQ + \frac{N_{aero}}{I_{zz}}$$

From this final result, note the effect of pitch rate (Q), yaw rate (R), and roll rate (P) on the aircraft response. For example, the product of P and R couple to produce pitch acceleration. This is commonly referred to as "inertial coupling." Loadings with greater pitch inertias (Iyy) generate greater inertial pitch up moments, allowing spins to stabilize at a more forward C.G. despite the greater aerodynamic pitch down moments inherent to that C.G. location. The DG-1000S ballasting system provides direct control over this inertia term, thereby permitting effective spin test training across the broadest-possible range of aircrew weights.

Finally, recall that one of the TPS learning objectives was to allow students to investigate control effects while in a spin. Given the wing-loaded nature of a sailplane, an aileron effects investigation provides an effective way to accomplish this. See Figure 8. In this tail-view of a sailplane in a left spin, imagine the mass distribution along the lateral axis to be something like a dumb bell, with each depicted mass following a circular path around the spin axis of rotation. With ailerons retaining some effectiveness in a spin, the aircraft will bank left when left aileron is applied, effectively pulling the two masses toward the center of rotation. Conservation of angular momentum dictates an immediate increase in the rate of rotation. From the pilot station, this appears as in increase in the time-rate-of-change of heading – often reported by the pilot as in increase in yaw rate. In the body axis frame of reference, however, the lateral input manifests itself as in increase in body-axis yaw and pitch rate. Paying careful attention to the sign conventions found in Figure 7, our finalized equations for $\dot{Q}$ and $\dot{R}$ confirm this.

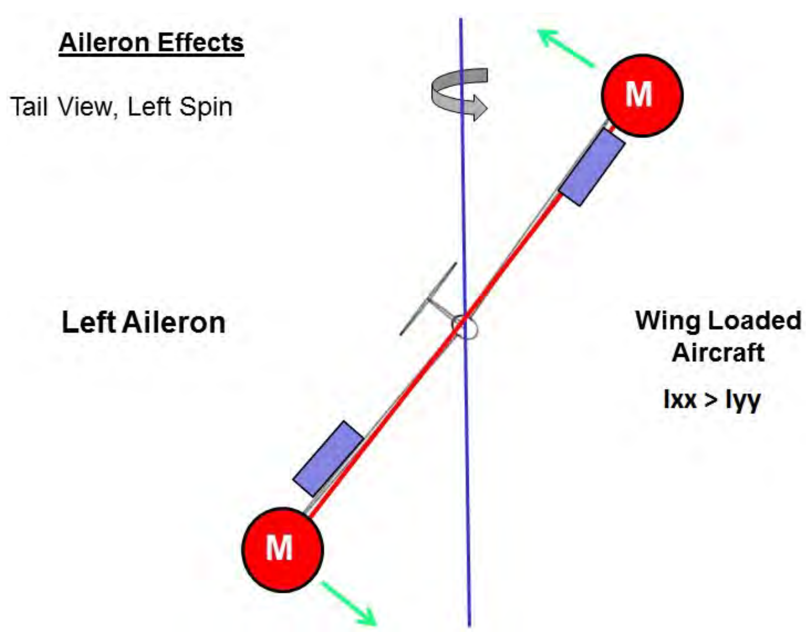

Figure 8. Aileron "Into" a Spin Increases Body-Axis Yaw & Pitch Rates for a Wing-Loaded Aircraft

RISK MITIGATION

Once understood, theory also provides a logical starting point for reducing the risks associated with planned out-of-control flight. At steeper attitudes (lower AOA), the airflow across the rudder has its greatest chord-wise component velocity, thereby generating greater rudder effectiveness. At the flatter attitudes expected with aft CG's and/or higher I_{yy}'s, the relative wind component is more along the vertical axis (span) of the rudder, which reduces its effectiveness. A sound build-up approach, then, would allow exploration of spin characteristics toward the edges of the intended loading envelope – without ever lacking sufficient rudder effectiveness to recover. This can be accomplished by working CG from forward to aft, and Iyy from minimum to maximum at each CG.

Figure 9 presents the DG-1000S CG and inertial loading envelope used for test planning. This envelope was constrained by the manufacture's certified maximum and minimum individual crew weight limits, maximum cockpit load, aircraft gross weight limit, and certified CG limits. The largest possible, or "theoretical" loading envelope could only be attained with extremely lightweight aircrew. The "test envelope" you see in Figure 9 was

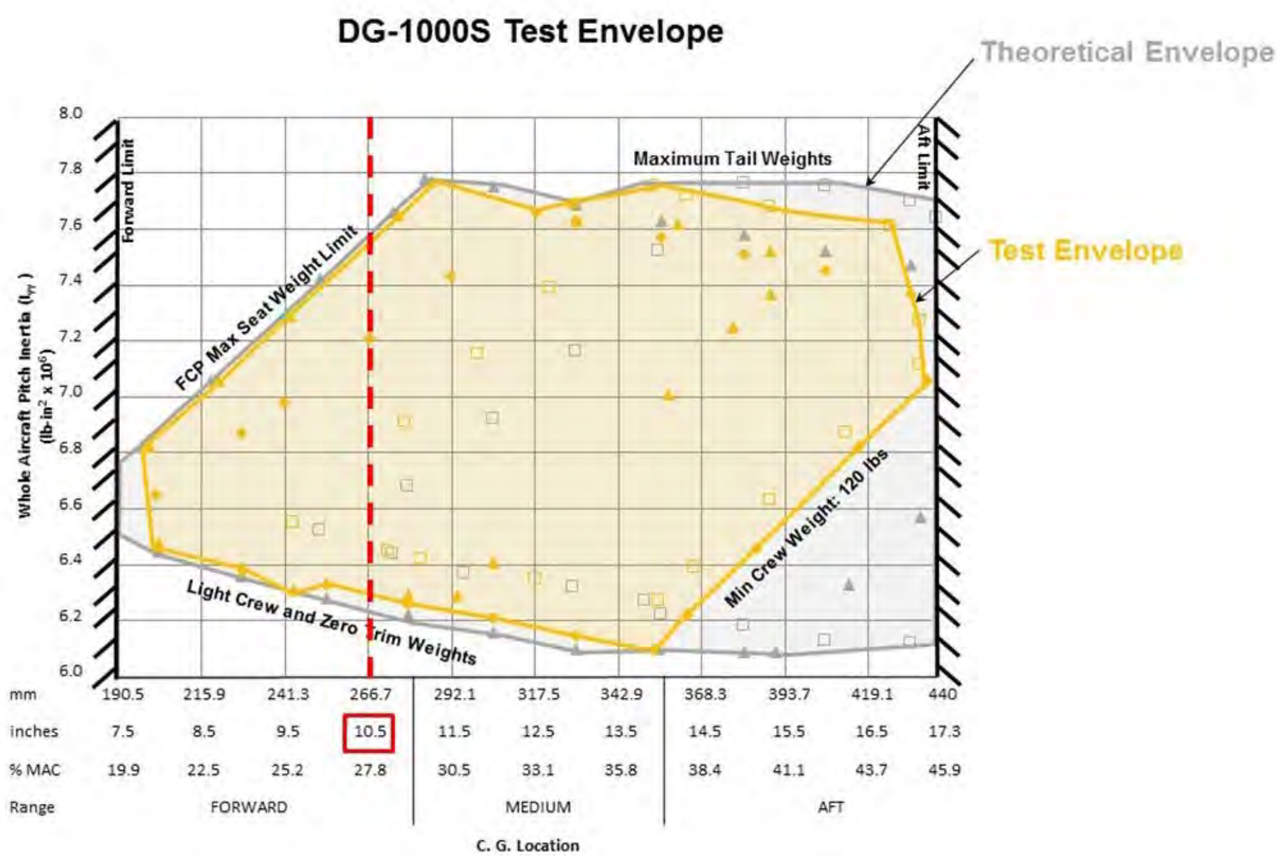

Figure 9. DG-1000S Loading Envelopes

representative of both project test pilot's (nearly identical) weight, including a parachute. With CG at/aft of approximately 13 inches, the largest and smallest possible I_{yy}'s could only be attained flying solo, with an appropriate selection of cockpit and tail ballast. At first glance, this may seem constraining on the user's requirement to conduct training with two aircrew. This was not the case, however: dual aircrew would simply operate more toward the center of the loading envelope – and often with less ballast. The test team's goal was to maximize the size of the tested loading envelope to provide the user greatest utility and safety.

A prudent starting point was to select a CG somewhat forward of where predictions suggested a stabilized spin was possible. For this project, recent spin test results on a similar aircraft – the DG-1001 – suggested starting at approximately 10 inches aft of datum, as depicted in Figure 9.[8] Next, a build-up increment of one inch was selected, working back to the certified aft limit of 17 inches. At each CG, the aircraft was first loaded to minimum-attainable I_{yy}, then maximum-attainable – essentially tracing the upper and lower edges of the test envelope seen in Figure 9. The test plan was written to allow a reduction in the size of build-up increments if early recoverability results suggested the need for a more conservative approach.

Forward CG's carry an additional type of risk for spin testing: structural failure due to over-speed/overload. After spin entry, if the aircraft's longitudinal stability is sufficient to push the nose down enough to un-stall the wing, airspeed and load factor will begin to build even if pro-spin control inputs are held. Commonly referred to as a "spiral dive," it must be recognized quickly in an extremely low-drag aircraft (like a sailplane) to avoid exceeding airspeed or load factor limits. A relatively recent SETP paper[9] presented by a sailplane test pilot – describing how he survived an in-flight break-up of his aircraft during a seemingly benign test point – underscored how easily limits could be exceeded should a maneuver not progress as planned.

Vetted test piloting skills, relevant experience and flying currency were obviously central to mitigating risk. While each project test pilot had substantial exposure to high-AoA test techniques, and decades of sailplane experience, neither had performed extensive (or recent) spin testing. This shortfall was addressed with pre-test flight training, first in an Extra-300. Training in the Extra focused on inverted spins: project pilots sought to learn how to combat the disorienting nature of such a maneuver over a prolonged period, as well as become familiar with respective susceptibility to the physiological "push-pull effect"[10] during dive pull-out – critical to preventing g-induced loss of consciousness. This was followed by acrobatics and spin training in the DG itself with an accomplished sailplane acrobatics flight instructor. Training here focused on controlling airspeed at extremely nose-low attitudes, and becoming comfortable with inverted handling qualities – essential to repeatable inverted spin entries.

Initially, calculating minimum safety altitudes for planned test maneuvers seemed straightforward. See Figure 10. Relying on previous testing of the DG-1001, the test team had a credible estimate of altitude lost during spin entry, during each turn of the spin and during any spin recovery procedure it happened to be investigating. Making the assumption that an alternate recovery procedure would fail to recover the aircraft, the pilot was given one second (or approximately 200 feet) to recognize this and transition to the flight manual recovery – which had a reported 100% success rate. Failing this, the parachute manufacturer recommended that aircrew be out of the aircraft, pulling the rip cord no lower than 1000 feet AGL to ensure full deployment before hitting the ground.

This left one question: from the time the decision to abandon the aircraft was made, to the time bailout actually occurred – how long would that take? A ground-based emergency egress test was devised: mean "time-to-bailout" for four test subjects was nearly 10 seconds – but with a large standard deviation, initially. As one would expect, repetition – developing "muscle memory" for this task – proved essential to reducing bailout time and variability. Test aircrew were required to refresh this muscle memory immediately before the first flight on every day of testing. While project pilots were eventually able to train to a bailout standard of 6 seconds or less, 10 seconds was ultimately used to leave margin for the unpredictable impact of wind blast, aircraft rotation – and adrenalin. This time period was divided by the known number of seconds per spin rotation, then multiplied by the known altitude loss per turn to arrive at a nominal altitude-lost-during-bailout figure. Terrain elevation was added to this (and the previously mentioned figures) to yield minimum test point entry altitude, minimum flight manual recovery initiation altitude, and minimum bailout altitude.

PRODUCING REPEATABLE DATA

Flight testing was divided into four phases. Phase I explored departure susceptibility using Phase A-D stalls, and the efficacy of the flight manual recovery following deliberate 2-turn spins. It also explored the widest range of CG/I_{yy} loading conditions: a "down-select" of loadings was made upon completion of this phase.

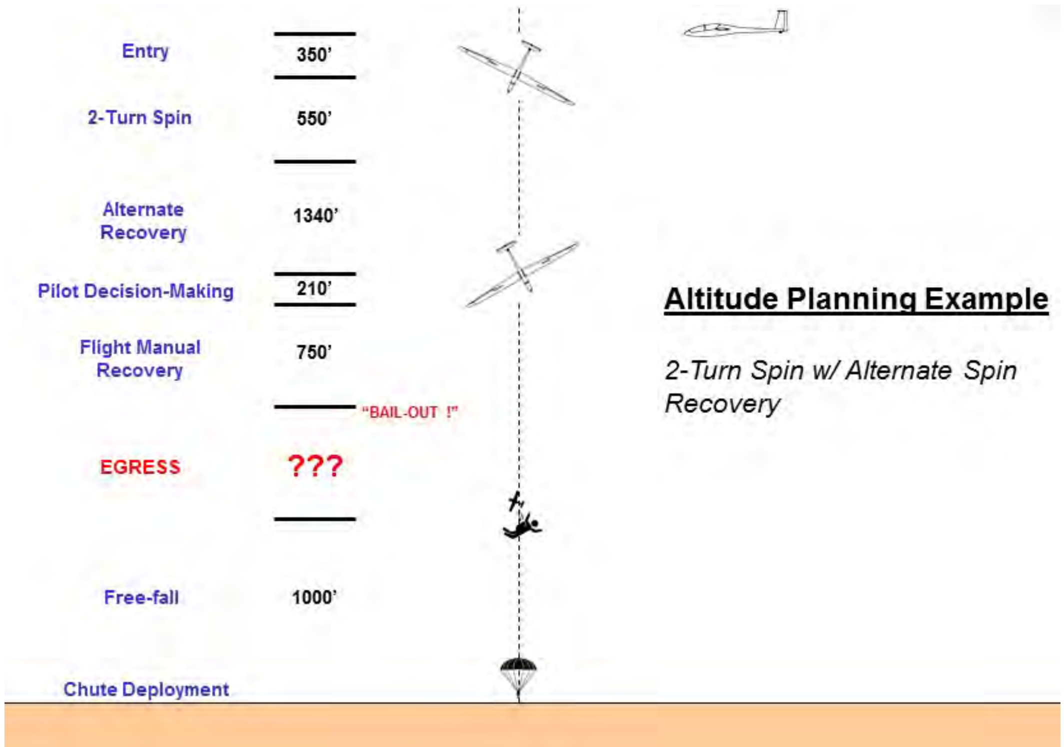

Figure 10. Planning Minimum Safety Altitudes

Only those loadings which reliably spun for two full turns (i.e. did not transition to a spiral dive) were down-selected for further examination in the remaining phases of test. Phase II was designed to explore the fully-developed spin phase during 5-turn spins. Phase III investigated aileron effects in the spin, four alternate spin recovery types, and two types of misapplied recovery controls. Phase IV investigated inverted spin characteristics during two-turn and five-turn spins. Phases I – III were also initially planned to investigate the two previously-described airspeed bleed rates for stall/spin entries.

All testing was performed in the 18m wing configuration, with landing gear and spoilers retracted. Each test point was performed three times to assess repeatability of results. Rudder inputs at the stall were attempted in both directions to check for left/right asymmetries in stall/spin characteristics.

1 kt/sec bleed-rate stall entries required a smooth, continuous increase in deck angle to the stall indication. 5 kt/sec entries could be consistently achieved with a more abrupt application of aft stick to a nearly fixed deck angle: this fixed attitude necessarily increased at aft CG's. Since lateral handling qualities tended to become "sloppy" in the DG-1000S near stall speed, careful attention to the yaw string was required for coordinated flight: anything less tended to cause the wing opposite the sideslip to drop first. Departure susceptibility data was obviously most repeatable in smooth air. Once the stall was recognized or rudder aggravation completed, all controls were abruptly neutralized; stick-fixed response was then evaluated against the pre-defined departure criteria.

Deliberate spin attempts were initiated using one of the stall entries described above. At the stall indication, ailerons were confirmed neutral, full aft stick was applied/held and full rudder abruptly applied in the desired direction of autorotation. These inputs were held for the pre-planned number of turns – or until a spiral dive was recognized. Should the latter occur, stick and rudder were smoothly neutralized while rolling to wings level, followed by a dive recovery. For spin recovery procedures, see Table 4. All began by confirming full pro-spin

Flight Manual	Misapplied Recovery Controls:	
	Incorrect Order:	**Elevator Only:**
• Full Pro-spin Rudder • Ailerons Neutral	• Full Pro-spin Rudder • Ailerons Neutral	• Full Pro-spin Rudder • Ailerons Neutral
• Rudder – Full opposite direction of spin	• Stick Steadily Forward	• Stick Steadily Forward
Pause	** Pause for 1 Second **	
• Stick – Ease forward	• Full Opposite Rudder	

Table 4. Published Spin Recovery Procedure Compared Against Misapplied Controls Investigations

rudder with neutral ailerons. The slight "pause" after applying full opposite rudder was designed to minimize yaw rate – and therefore inertial coupling – before attempting to break the stall with forward stick. (Recall Figure. 6)

While it was not practical to investigate every permutation of pilot error when attempting to recover, two types were examined. The first ("Incorrect Order"), reversed the order of the elevator and rudder input – and invited increased inertial coupling for one second. As a build-up, this procedure was always attempted first. The second misapplied controls procedure ("Elevator Only") was expected to provoke near-worst-case inertial coupling, in that pro-spin rudder was held as elevator simultaneously pushed the nose down.

As their names imply, three of the four planned "alternate" spin recovery procedures were straightforward. All controls were neutralized (and held) during the "Controls Neutral" recovery, while all controls were released and allowed to "float" for the "Hands Off" recovery. The "Rudder Only" procedure called for full-aft stick, ailerons neutral – while applying full anti-spin rudder. The recently re-named "NACA-Modified"[11] procedure required a simultaneous neutralization of elevator with full anti-spin rudder. Again, to conduct a meaningful comparison between each recovery type, all recovery inputs needed to be applied consistently: this was accomplished with abrupt, step-like inputs.

Only the Flight Manual recovery was used during recovery from inverted spins (with elevator inputs reversed, obviously).

All spin recovery attempts were considered successful and complete when rotation ceased and airspeed began to increase; a dive recovery followed.

TEST RESULTS OF INTEREST

Understanding the Data

Figure 11 provides an example time-history plot of maneuver data. If viewing in black-and-white, the slightly darker time-history traces correspond to the left-hand y-axis parameters. (In color, these appear blue) Lighter traces (or green) correspond to right-hand y-axis parameters. Pitch and roll angles/rates are body-axis values. While instrumentation was capable of measuring body-axis yaw rate, time histories present what the student would perceive during spin test training: heading and heading rate. Velocity and load factor time history plots appear in Figures 12 -15: it's important to remember that the velocity trace presents MEMs-derived inertial data*:* it does not depict Pitot-static airspeed. Therefore, in the following discussions, references to a fluctuation in airspeed may not be evident in the corresponding time history plot of inertial velocity. Airspeed fluctuations were reported based on post-flight review of cockpit video. Note that AHRS heading angle is displayed between ±180 degrees: the transition between + 180 degrees and – 180 degrees as the aircraft rotates gives this trace a "saw-

tooth" appearance. Data was sampled at a rate of 10 Hz. "Entry 1" refers to a 1 kt/sec bleed-rate stall/spin entry, where "Entry 2" refers to a 5 kt/sec entry.

Phase I

The DG-1000S stall indication was consistently marked by reaching full aft stick. During the progression of Phase A-D stalls using Entry 1 – following the described CG/I_{yy} buildup – departures were first observed at 13 inches aft-of-datum during Phase C stalls. I_{yy} did not affect departure susceptibility as much as first anticipated. With Figure 11 as an example, heading rates remained steady after neutralizing controls long enough for departure criteria to be exceeded (in this case, heading change > 90 degrees) with CG's between 13 – 15 inches. This rendered the aircraft "resistant" to departure in this CG range, and "extremely resistant" at all other tested loadings. Entry 2, however, did not provoke a departure until deliberate spins were attempted; in other words, the aircraft was rated

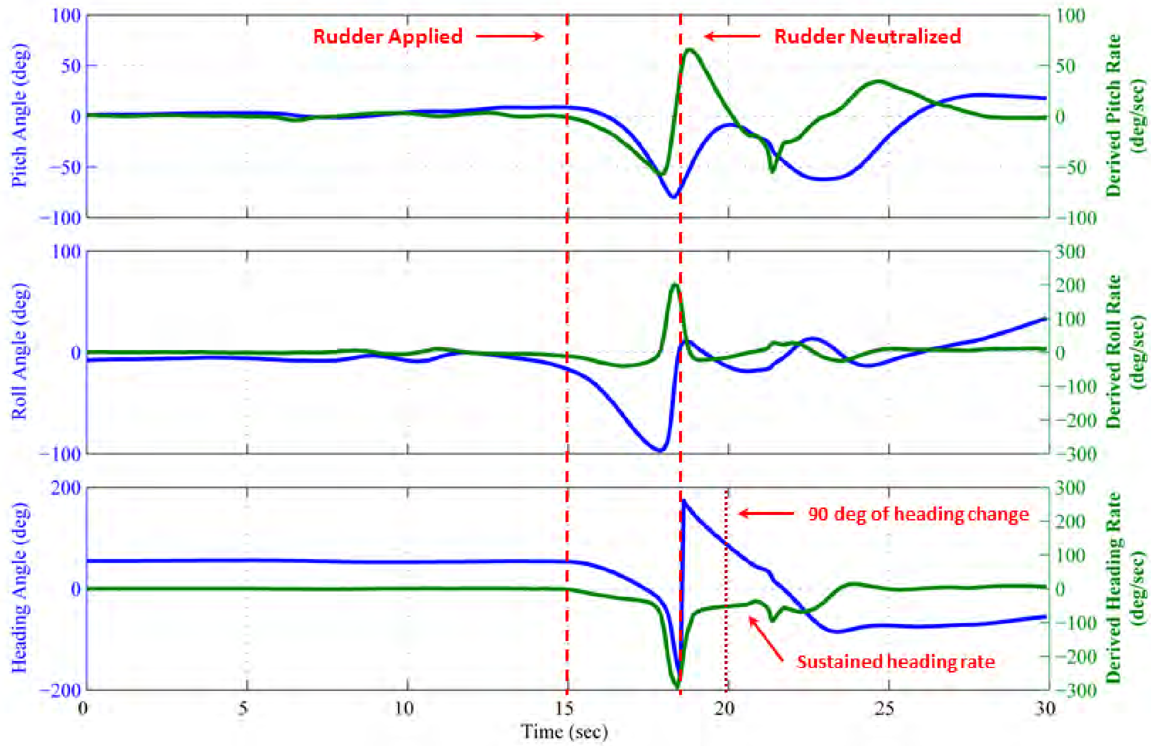

Figure 11. Departure Following a Phase C Stall

"extremely resistant" to departures at all tested loading conditions using this entry. The entry's higher pitch attitude led to substantially reduced airspeed at the stall indication – leading to reduced rudder effectiveness at the stall. Stated another way, the Phase C stall's three seconds of rudder aggravation wasn't as "aggravating" using the 5 kt/sec entry.

The impact of stall entry type can be seen more clearly in Figure 12. It provides a direct comparison of aircraft response during two-turn spins – at the same loading conditions – for each entry type. While the two spins depicted occur in opposite directions, this is inconsequential: upright left-hand spin characteristics were ultimately found to be identical to right-hand upright spins. The rudder's reduced effectiveness at the stall is clearly seen for Entry 2, in that heading rate development occurs nearly 3 seconds later than that seen during Entry 1. Another key difference is seen when comparing each spin after 180 degrees of rotation: as the aircraft pitches down to nearly vertical, the 1 kt/sec entry leads to a momentary "spike" in load factor (~2 g's), where the 5 kt/sec entry oscillates at an accelerated condition for nearly 3 seconds. While the nose pitches back up at this point for both entry types,

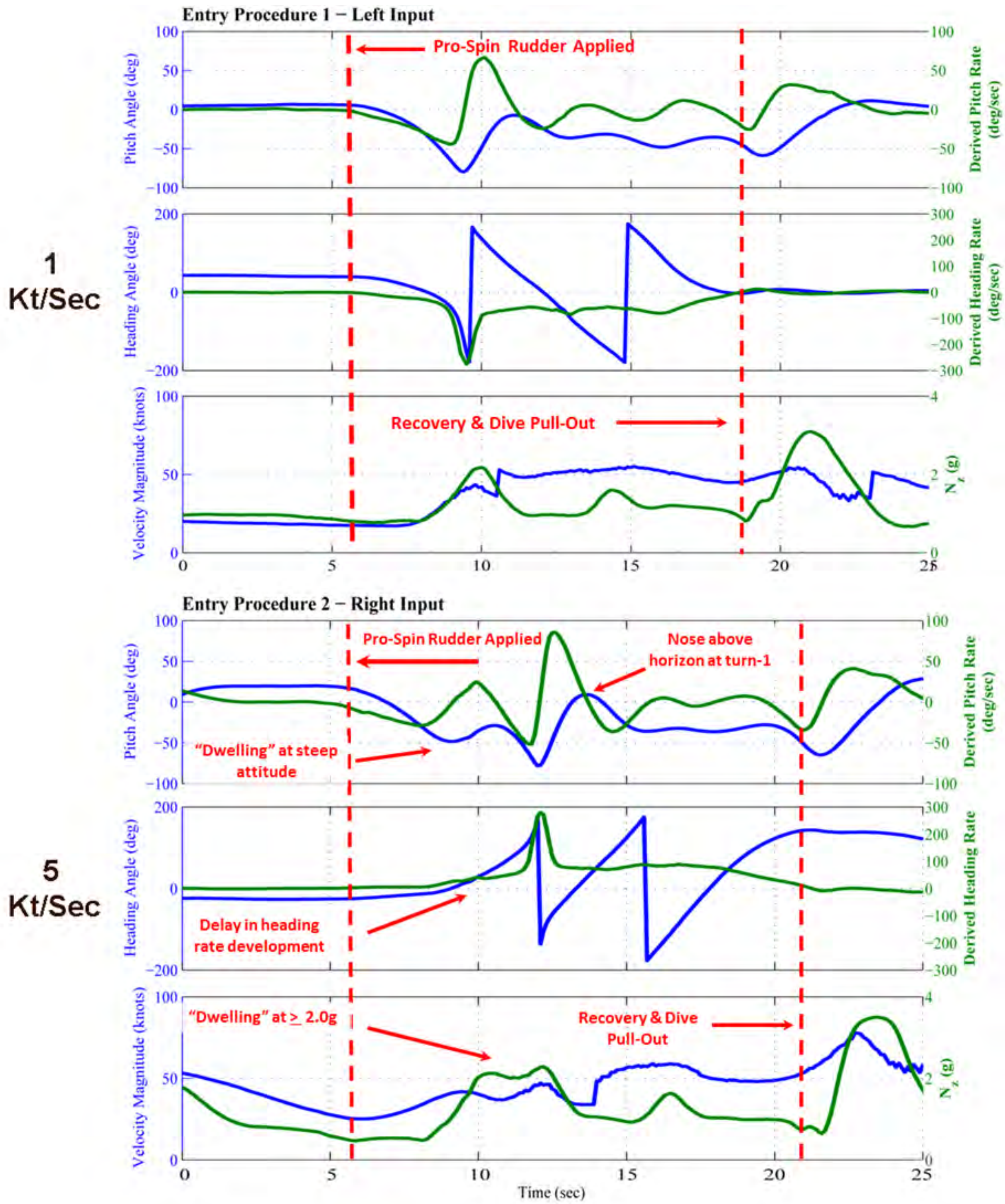

Figure 12. The Impact of Stall Entry on 2-Turn Spin Response, Identical Loading Conditions

the 5 kt/sec entry often led to much more dynamic pitch-ups – reaching attitudes as high as 20 degrees above the horizon at completion of turn-1.

As one might expect, then, more dynamic stall/spin entries led to more dynamic incipient spin phases. What was unexpected, however, was the response seen during turn-2: both entries show essentially the same oscillatory behavior, where the 1 kt/sec entry was expected to settle more quickly to a constant pitch attitude and heading rate – i.e. settle more quickly toward a fully-developed spin phase.

Only loadings at/aft of 12 inches aft-of-datum reliably spun without transitioning to spiral dives: 12 – 17 inches aft-of-datum, then, became the down-selected range of CG's for the remaining phases of test. In that the test team felt there was nothing useful left to learn from various stall entry types, the 5 kt/sec entry was also dropped after Phase I.

Phase II

As the test team moved in to this phase of testing, it was looking for at least a developed (if not fully-developed) spin: without this, students would never be afforded the opportunity to assess traditional spin mode modifiers. Because this never occurred during 2-turn spin testing, the team could only hope to converge to near-constant attitudes and rates at some point beyond the second turn.

It was not to be – see Figure 13. It depicts an upright 5-turn spin at the aft CG limit. Upright spins were assessed as "highly oscillatory" by both project pilots, technically never developing beyond the incipient phase. While the period of oscillation was 8-9 seconds, the rotational period was only 5-7 seconds: this meant that on a strict "turn for turn" basis, the aircraft rarely showed the pilot the same thing twice. The opposing aerodynamic and inertial forces (discussed previously) never achieved balance at tested conditions. Across the tested loading envelope, the attitude modifier varied from "flat" to "extremely steep," while rate varied from "slow" to "extremely rapid:" no single attitude or rate modifier could ever be assigned.

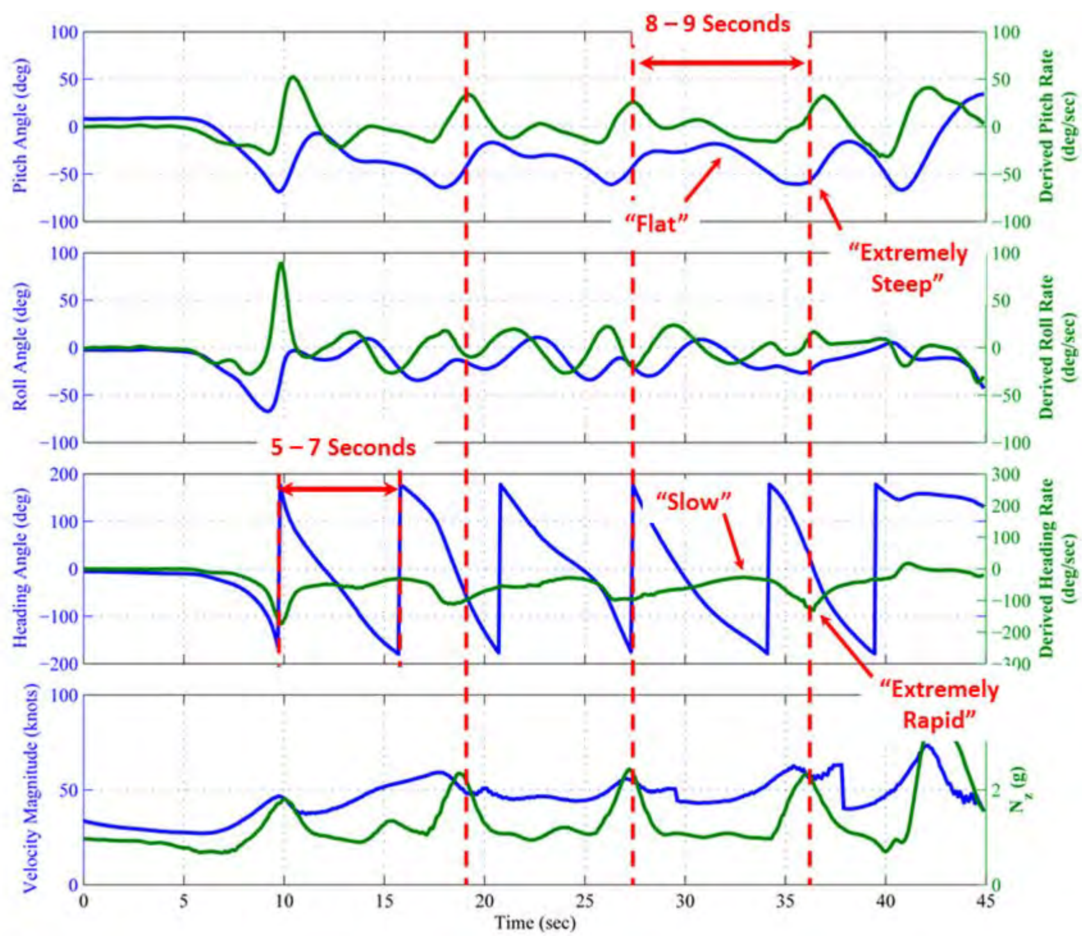

Figure 13. 5-Turn Upright Spin: Oscillation vs. Rotation Period

A closer look at Figure 13 shows that load factor spikes occurred when pitch attitude was at its steepest: combined with the increasing airspeed that was observed at that moment, the indications were more consistent with a spiral dive – not a spin. If pro-spin inputs were maintained, what followed was described by project pilots as a “snap roll on a vertical down line:” roll/yaw rates sharply increased at peak load factor, “throwing” the nose back up toward the horizon. Load factor then dropped back to 1.0, and airspeed diminished: indications consistent with a spin, not a spiral. As Figure 13 illustrates, this cycle of “spiral-like” and “spin-like” behavior continued for as long pro-spin inputs were held.

If a spin recovery was attempted during the spiral-like portion of an upright spin, when heading rate was at its highest, another unexpected dynamic emerged: rudder-lock. It announced itself with noticeably increased pedal forces while attempting to apply opposite rudder for spin recovery. Recall that rudder lock occurs following vertical fin stall: the local relative wind exceeds the vertical fin’s critical angle of attack. This leads to flow separation, and can create a pressure gradient sufficient to hold the rudder against the stop – in this case, in the pro-spin direction.

This was cause for some concern. Conducting a valid comparison between various spin recovery procedures called for abrupt application of opposite rudder. Given the heavy pedal forces, the obvious concern was for the dynamic load on the aft fuselage, vertical tail and/or rudder hinges. With the center of pressure of the vertical tail a few feet above the fuselage centerline – where the fuselage was only several inches in diameter where it joined to the tail – there was concern over exceeding the ultimate torsional load limit at that location and (quite literally) twisting the tail off of the aircraft.

The risk was not merely hypothetical: abrupt rudder inputs immediately following transition from a spin to a spiral dive caused this exact structural failure mode during a 2003 sailplane spin certification test flight. In the wake of this mishap, the Federal German Accident Investigation Bureau made a formal recommendation to the European Aviation Safety Agency (EASA) to “incorporate maximum possible aerodynamic loads resulting from a combination of rudder deflection and yawing condition into the certification specifications for designs of vertical fins for sailplanes. . .”[12] The problem: this recommendation was published in 2009. The DG-1000 was certified for spins in 2001.

While all test points were performed within the certified limits of the aircraft, prudence dictated a modified approach to spin recovery in the presence of rudder lock. Either: 1) opposite rudder was applied smoothly and slowly – to minimize dynamic loading – or, 2) abrupt application of opposite rudder was delayed approximately ½-turn to allow the nose to pitch back up into the “spin-like” portion of the oscillation cycle – where no rudder lock was observed.

Phase III

All evaluated spin recovery procedures – even those involving misapplied controls – ultimately proved highly effective. As expected, the “Elevator Only” misapplied controls procedure provoked worst-case recovery characteristics, due to inertial coupling. Yet even here, autorotation only continued for one full turn after forward elevator was applied.

The magnitude of the inertial response to aileron inputs during a spin was notably affected by the timing of the input: heading rate was most visibly increased with pro-spin aileron while the aircraft was in or near the “spiral-like” portion of the oscillation cycle.

Interestingly, both the aileron effects demonstration and hands-off recovery usually left the aircraft in a high-sideslip condition at cessation of autorotation – with rudder lock. Again, to minimize tail loads, rudder was smoothly neutralized at this point to eliminate sideslip prior to dive pull-out.

Phase IV

Inverted spins were initiated from stable, coordinated, un-accelerated (-1g) inverted flight. Only 1 kt/sec entries were used. Due to wing camber, inverted spin entries occurred 20 – 25 KIAS faster than upright entries. Both 2-turn and 5-turn spins were performed at down-selected loading conditions: this meant that inverted spin testing was commenced at a CG which was 3 inches further aft than where upright testing began. This was per the planned test build-up, as Phase I testing suggested that an inverted spiral dive – not recoverability – was the greater probable threat to safety at CG's forward of 13 inches.

Figure 14 depicts the primary inverted spin mode. It too was rated "highly oscillatory," with load factor spikes reaching nearly -3.0g at the height of the "spiral-like" portion of the oscillation cycle. Unlike the upright mode, however, the oscillation period was less than the rotational period – approximately two cycles per rotation. (See the derived pitch rate trace in Figure 14) The attitude modifier varied from "Steep" to "Extremely Steep."

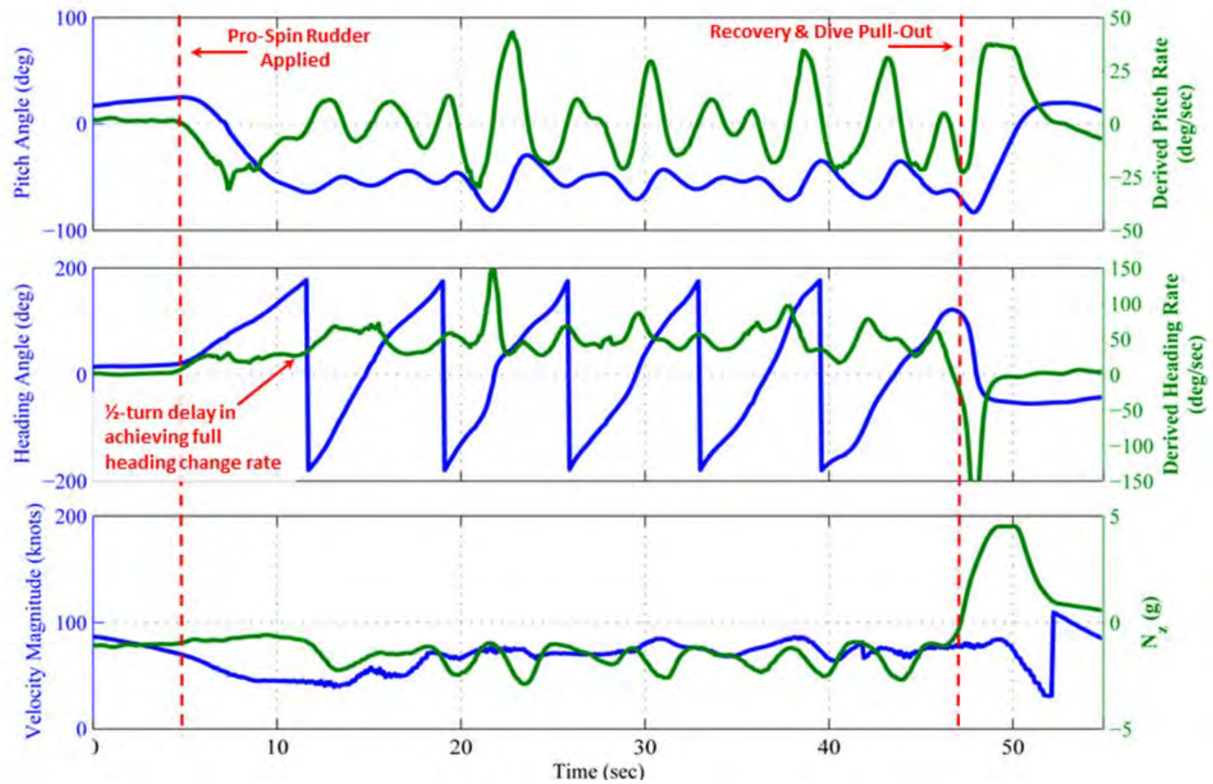

Figure 14. 5-Turn Oscillatory Inverted Spin Mode – to the Left

As one might expect, the mode was both disorienting and uncomfortable. The magnitude of the negative-g "spikes" were largest at forward-most CG's: increased longitudinal stability put the nose down slightly lower and longer, resulting in increased airspeed just before the recurring accelerated stall. While the aircraft was certified to -5.0g, negative load factors in excess of -3.0g were considered unsuitable for training – and therefore not worth the risks inherent to testing them. G-spikes at forward CG's posed a problem for the planned test build-up approach – which will be further addressed shortly.

A large majority of the inverted spins flown behaved as depicted in Figure 14. But one day, without warning – and at precisely the same loading conditions – an entirely different spin mode surfaced. See Figure 15.

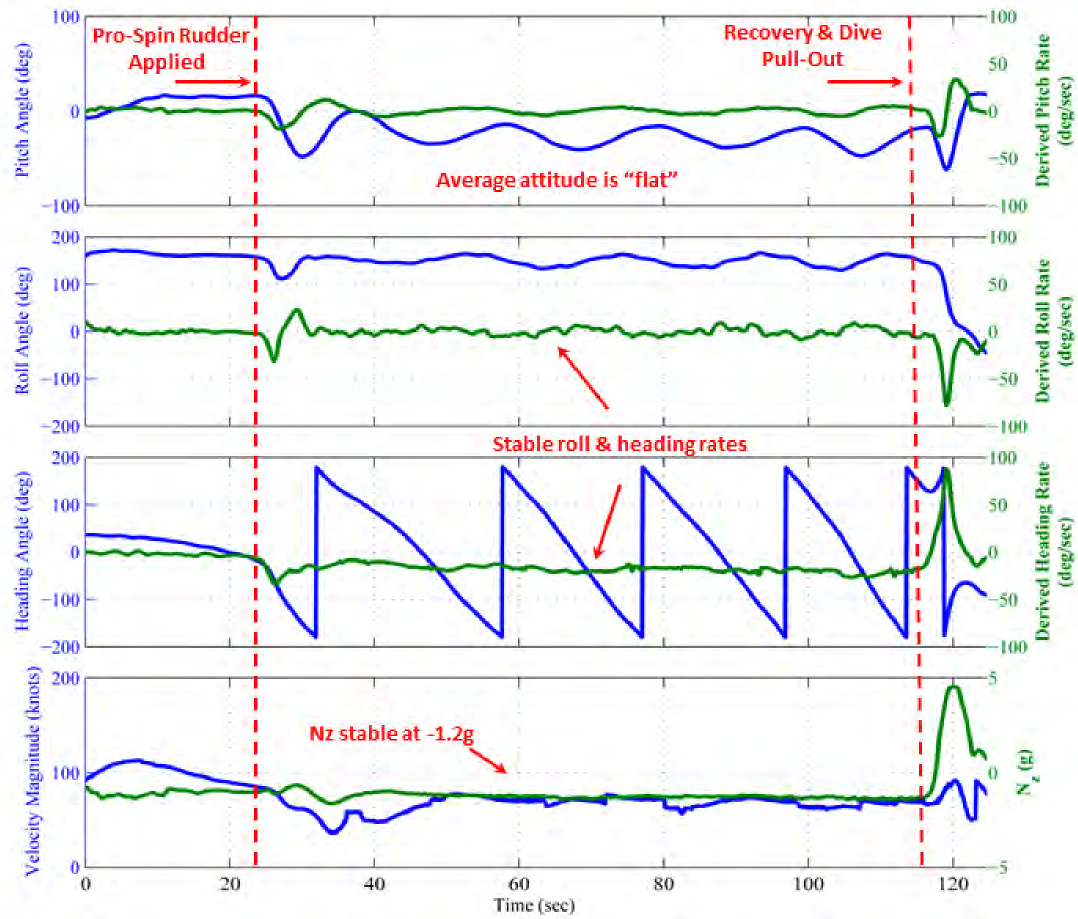

Figure 15. 5-Turn Smooth Inverted Spin Mode – to the Right (note loading is identical to Fig. 14)

This was – by far – the smoothest spin mode encountered during the program: note that pitch/roll/heading rates, as well as the load factor trace are nearly straight lines. Rate was extraordinarily slow: one rotation required 18 seconds to complete, on average. Inverted 5-turn spins lasted for over 1 ½ minutes. This was also the flattest spin observed during the program. Even stranger, it was later discovered that the oscillatory inverted mode could transition to this smooth mode – but never the reverse.

Unexpected inverted behaviors did not end there: two additional smooth modes emerged. Unlike the mode depicted in Figure 15, however, these were "Steep," with a rotational period of seven or eleven seconds, respectively. All three smooth modes had one thing in common: they only occurred when spinning to the right. After many attempts, project pilots were unable to provoke a smooth mode with left rudder applied at the stall. Smooth modes also only occurred near the aft CG limit (16-17 inches). In other words, while attempting right-hand inverted spins in this CG range, the test team was unable to reliably reproduce any one of four possible modes at will.

These unexpected spin modes are not likely attributable to an asymmetry in mass distribution: such an inertial asymmetry would likely surface in upright spin test results as well. As previously mentioned, it was not viable for the test team to modify the aircraft to gather the external air data which would likely explain these results – nor was it considered in-scope for the project.

RECONCILING RESULTS TO REQUIREMENTS

Of the five original TPS student learning objectives, the test team's original conclusion was that the DG-1000S proved an effective spin test trainer for three of them: 1) Determining the aircraft's MIL-F-83691B susceptibility to departure, 2) Investigating the efficacy of various spin recovery procedures and 3) Investigating control effects while in the spin. Departure susceptibility training was a potential strong-suit for the aircraft, in that it illustrated how various stall entry methods could produce different susceptibility ratings – at the same loading conditions. As previously reported, the aircraft was not most departure-susceptible at aft-most CG's, as classroom theory might suggest: while the data to definitively explain why was not available, the test team saw value in exposing students to the unpredictable nature of the real-world flight test environment. In this vein, the team also saw excellent learning value in inverted spin test training: the unpredictable emergence of various inverted modes, and the opportunity to learn to make accurate observations in a much more disorientating flight environment could better-prepare future test pilots for the unexpected departures they might encounter.

Per the strict MIL-F-83691B definitions, achieving two of the TPS desired learning objectives appeared problematic: 1) Identifying spin phase boundaries and 2) Assigning spin mode modifiers. Because attitude and rate modifiers were never the same on a strict "turn for turn" basis, the aircraft never attained the fully-developed phase. Moreover, these two modifiers spanned the full range of defined ratings. A student could simply guess at a particular rating following a simulated spin test point, and – at least once during the maneuver – their guess would be correct. This called the team's attention to the last of the four spin mode modifiers: "Oscillations." The "Highly Oscillatory" and "Violently Oscillatory" ratings seemed to anticipate the possibility of widely varying attitude and rate modifiers – without resolving the dilemma of how to assign them under such conditions.

All of this led the team to begin to question whether the aircraft was deficient as a spin test trainer, or if the traditional means of classifying spin behavior was, in fact, deficient. The rationale was simple: a robust scheme of classification should be able to capture the full range of observed behaviors. With the DG-1000S seeming to defy classification, a broader, more inclusive set of conventions was proposed:

First, if a range of observed attitudes and rates are bounded and unchanging from one recurring oscillation cycle to another (as Figure 13 clearly shows) -- i.e. "cycle to cycle," not necessarily "turn to turn," as the MILSTD specifies -- might it be reasonable to also call that a "fully developed" spin? If it were, the team proposed that the "developed" phase could simply be marked by the moment the axis of rotation became perpendicular to the earth, and the fully-developed phase boundary could be marked at the moment the period of the recurring oscillation cycle could be identified. Then, if the oscillations assessment is "highly" or "violently" oscillatory, attitude and rate modifiers would not be assigned: instead, the observed ranges of attitudes and rates would be reported. Such a classification scheme would allow a full description of observed DG-1000S spin mode characteristics without significantly changing how TPS challenges or develops a new test pilot's observational skills.

Within this construct, the DG-1000S begins to look more viable as a spin test training aircraft – but with two qualifiers. First, dynamic ranges of attitudes and rates are initially more difficult to discern than fixed values. Second, real-time recognition of the need to modify spin recovery technique to minimize tail loads consumes additional cognitive "bandwidth" – in a flight environment which is notorious for producing sensory overload. For these reasons, the DG-1000S may not be an optimal aircraft in which to begin spin test training: learning may be better served by exposing students to less dynamic spin modes first. At this writing, TPS is considering options to achieve these ends.

LESSONS LEARNED

In addition to implicit lessons-learned presented thus far, we feel the following learning points deserve emphasis. While a few of them are admittedly philosophical in nature, <u>all</u> are derived from *specific* events that occurred before, during or well-after testing was complete.

1. **<u>Emergency Bailout Considerations.</u>** We were somewhat surprised by how long it took to get out of the aircraft during our ground bailout test: our initial guess for bailout time from the DG-1000S was 5 seconds. Ground test results led us to double that figure. Don't *think* you know how long it takes to get out of your aircraft: <u>know</u> – as best as you practically can. We eventually reduced average bailout time by approximately 50% – through a considerable amount of practice. Published SETP papers underscore the importance of this kind of hands-on rehearsal before exposing yourself to a potential real-world bailout situation.[13]

2. **<u>Pre-Test Training.</u>** The primary project pilot had 20 years of test experience and nearly 35 years of experience as a licensed glider pilot: it would have been very easy to dismiss the need for pre-test glider acrobatics and spin training before commencing test. Yet the training we accomplished was the single most important step we took to mitigate safety risk: it enabled us to remain oriented and aware of what the aircraft was doing under significantly disorienting conditions, leaving us spare cognitive "bandwidth" to recognize subtleties – like the differences between "spin-like" and "spiral-like" behaviors, or the need to adjust the phasing of rudder inputs to minimize tail loads.

3. **<u>Test Configuration Control.</u>** As mentioned in the introduction, past SETP papers have emphasized the impact seemingly small aberrations in the aircraft mold line can have on high-AoA characteristics. While isolating and controlling variables is central to any effective test, we suspected these types of aberrations could prove especially problematic while testing an aircraft as aerodynamically efficient as a high-performance sailplane. In this regard, the DG-1000 did not disappoint.

   We began with a control-rigging check. While all control surfaces were rigged within manufacturer's tolerances, variations were noted. Two post-production modifications near the nose of the aircraft – a nose skid and a canopy repair bracket – were also documented. The main landing gear doors were held closed in flight with a simple bungee system – which was not especially effective at high sideslip angles. The relative wind would snap one door open (intermittently) during spins. See Figure 18. While the doors were relatively small and near the aircraft CG, we confirmed proper installation of the bungee system nevertheless – and ultimately concluded that the unsettlingly-loud cycling of gear doors during a spin constituted production-representative behavior.

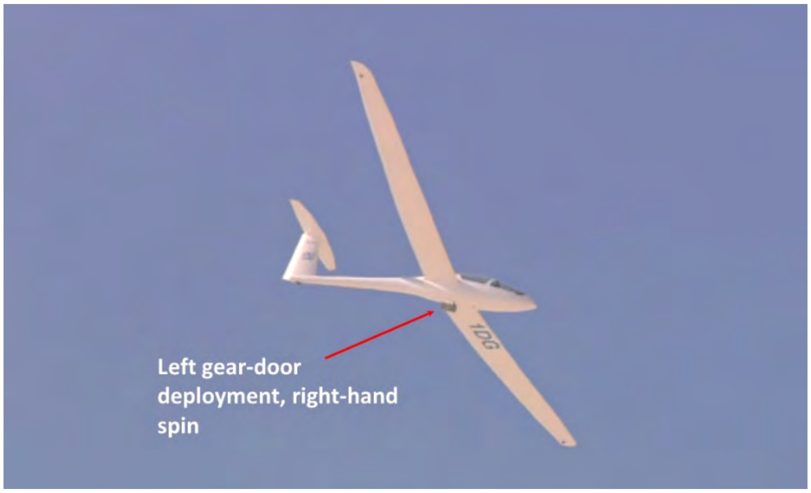

Figure 16. Intermittent Landing Gear Door Cycling

   Unexplained lateral biases surfaced during early departure-susceptibility testing. One day the aircraft would tend to roll-off to the left at the stall indication; the next day to the right – at identical loading conditions. While even the lightest turbulence can cause this in a sailplane, the biases were still noted in perfectly smooth air, shortly after sunrise. Two possible causes were identified. Chord-wise gaps – several millimeters wide –

exist at each wing root, at the location where each removable wing is attached to the fuselage. Left uncovered, these gaps would allow higher-pressure air from the lower wing surface to blow the upper surface, causing substantially large flow-separation “bubbles” near the wing root. While these gaps are normally closed with tape, it becomes brittle and splits over time: when this happens asymmetrically, the wing lift distribution loses its symmetry as well. Secondly, dirt and smashed insects are also known to induce asymmetric separation bubbles on a sailplane’s wings. By verifying air-tight wing-root tape and carefully cleaning the wing surfaces each morning, the previously-observed lateral biases virtually vanished.

While admittedly speculative, we believe one or more of the factors discussed in this section may have played a role in our unexpected test results. On the assumption that flow visualization tools – like tufting – do not significantly alter high-AoA aerodynamics, finding explanations for these results may be possible. Given our test training requirement, however, spending the time and money to gather such data – interesting as it no-doubt would be – was ultimately deemed unnecessary: the primary focus of the planned curriculum event was *execution* and *observation.*

Here are the lessons-learned: 1) at the very least, our successful elimination of lateral bias during departure susceptibility testing confirmed past SETP lessons-learned: minor mold line aberrations can indeed have notable impact on high AoA test results. 2) Tailoring your test to user requirements means that you must effectively identify, isolate, control and/or measure those variables that affect the achievement of test objectives – nothing more or less. While this may seem obvious, recent SETP papers[14] suggest that testers and program managers alike struggle in this area.

4. **Selecting a Build-Up Approach.** The progression of test conditions we used – from forward-to-aft CG and minimum-to-maximum I_{yy} – is a common approach to spin testing. Recoverability is the obvious driver. But the more forward the CG, the more “spiral-like” both upright and inverted spins became, where “spiral-like” behaviors led to rudder lock and structural concerns for the vertical tail. Negative load factor “spikes” during inverted spin testing were also greatest at forward-most CG’s – where we had 2g’s less margin available before exceeding certified limits. With a recent SETP paper illustrating how easily glider test pilots could inadvertently exceed ultimate load limits – and realizing that some structural failure modes could place the aircraft in a condition that was difficult (if not impossible) to bailout from – we stood-down from testing on multiple occasions to consider modifying our build-up. While preliminary test results strongly suggested that recoverability would not be a significant factor for this aircraft, modifying a foundational, formally-reviewed and approved safety build-up – in the middle of a test program – was no trivial matter.

   Spin mode prediction tools – assuming any are practically available to you – may not correctly identify worst-case test conditions. A recent SETP spin paper describes a test team selecting what they believed would be a benign test configuration for a start-point in their build-up – only to ultimately learn it was one of the worst-case configurations.[15] The learning points here: 1) spin recoverability at your aft-most-CG may not, in fact, represent your most serious test hazard, and 2) at the risk of sounding trite, build flexibility in to your safety buildup – commensurate with uncertainty in pre-test predictions.

5. **Testing Certified Aircraft.** As the USAF learned from the 1989 Precourt spin test, published flight manuals for certified aircraft may not tell the complete story. There was absolutely nothing in the DG-1000 flight manual to suggest we would encounter multiple inverted spin modes, for example. In that none of the inverted modes proved unrecoverable, the manufacturer may not have felt them worthy of comment, given the anticipated needs of most users – assuming the manufacturer even observed more than one inverted mode.

   It’s safe to assume that JAA certification criteria did not contemplate an aircraft like the DG-1000S being used for *flight test* training. For example, the non-flight-manual spin recoveries we investigated were not evaluated during certification testing.[16] If you encounter a plan to use an aircraft in such a fashion – and *don’t* hear about a commensurate plan to test – we respectfully submit it’s time to *speak up*: historically, the cause of aerospace development is not well-served when placed in the hands of an un-vetted, un-trained or unwitting test pilot. If this were not so, our test pilot schools could have closed their doors long ago. As long as there

are aerospace vehicles, experimental flight test will remain relevant: in the experience of this test team, ensuring others understand this may be *another matter entirely*.

6. **The Dilemma of Classification.** Before you dismiss us as apostate for daring to propose a redefinition of decades-old MILSTD spin classification conventions – so that they might accommodate our test results – it's worth remembering that nature has a decidedly inconvenient way of defying any classification scheme we may invent. An alternative approach would have been to simply conclude that the DG-1000S never really spins at all: it merely *starts to* – before coming partially un-stalled. But given that load factor and airspeed only momentarily increase during the "spiral-like" portion of the oscillation cycle, we ultimately decided that this was not an accurate characterization.

   Again, the most useful classification scheme is one which can characterize the full gamut of possible outcomes – and is standardized throughout the using community, so that we can communicate with each other unambiguously. We submit, then, that the formal cancellation of MILSTD's like MIL-F-83691B was not helpful to the cause of standardization. In their absence, professional organizations like SETP, SFTE and AIAA can help meet the pressing need to propagate updated classification conventions when the need arises, thereby restoring some degree of standardization across the industry.

7. **Kelly Johnson Was Right.** TPS leadership assembled a very small team for this effort. In 21 flying days, that team executed 147 test missions and over 800 test points – with a ground and flight test crew rarely larger than four people on any given day. This was well outside the norm for most of us, and led to some soul-searching when we first contemplated the elevated-risk portions of the program. With fewer people on our team, we knew there would be less cross-checking of each other's work within their respective specialties . . . more opportunities for errors of omission to go undetected. An unspoken, yet recurring question was: "Do we have the right people for this effort, and . . . *am I one of them*?"

   Many are familiar with the story of Kelly Johnson, and his ingenious development efforts that led to aircraft like the P-38, P-80, U-2 and SR-71. Perhaps not as well-known are his "Fourteen Rules and Practices" for such development efforts.[17] Rule #3 reads:

   "The number of people having any connection with the project must be restricted in an almost vicious manner."

   His rationale is not hard to understand: smaller teams give each member better visibility on each other's work – hence, better overall awareness of all aspects of the program. Communication is simplified and there is a greater chance for close team cohesion to develop.[18] But rule #3 does not end there – Mr. Johnson adds:

   "Use a small number of ***good*** *people (10% to 25% compared to the so-called normal systems)."*

   Given the inherent reduction in checks and balances of a small team, the operative word here is "good." While that word may mean different things to different people, it necessarily takes on a specific meaning within the context of elevated-risk flight testing. Independent of the other criteria we may feel beholden to, we must ask ourselves this: "Of all available choices, is this prospective team member the most *capable* – and most *willing, independent of personal self-interest* – to do what is required to help the team succeed?" Stated another way, we humbly submit that the unforgiving nature of flight test does **not** afford us the indulgence of doing anything less than putting our best-possible foot forward. While you may not always be in a position to determine the size or composition of your test team, you certainly have the ability to respectfully remind program management of proven best-practices. Our experience with this project suggests that doing less would have been dismissive of the dangers we faced. This leads to our final – and perhaps most important – lesson-learned.

8. **Defeating Dismissiveness.** For reasons we do not pretend to fully understand, say the word "glider" or "sailplane" to a flight tester . . . and in many cases, prepare for a prominent display of dismissiveness. We

were not immune: this tendency haunted us throughout the program. Yet, apart from power effects, our experience with the DG re-confirmed that a sailplane illustrates the most important aspects of spin testing – including the potential hazards. At least in part, this is why TPS has trained with them for over 20 years.

We found the dangers of dismissiveness to be insidious: generally, no *individual* who wants to be taken seriously within engineering circles overtly asserts that our attentions should vary based on whether or not the test item happens to have an engine, or by the pound of aircraft gross weight, knot of airspeed or dollar-cost. Rather, the effects of dismissiveness often seem veiled within a team's *collective* decision making.

Dismissiveness can nullify every bit of careful planning, knowledge and skill your team can muster. In spite of its insidious and potentially lethal nature, however, we submit it can be defeated. Based upon the specific forms of dismissiveness we encountered, we close with the following:

a. <u>YOU are a "Keeper of the Flame."</u> As new technologies emerge, the list of flight test topics we must understand necessarily grows – each discipline competing for our attention. As the field becomes increasingly crowded, some seem tempted to dismiss the lesser-seen disciplines. Yet there is a false premise at work here: many topics within the field of flight test are rarely seen . . . shall we dismiss them all? We submit that the relevance of a particular test discipline is not exclusively measured by its frequency-of-use, but also by the degree to which it measures *foundational airworthiness*. The need for spin testing shows no sign of vanishing any time soon: someone is going to have to do it. Keeping in mind the inherent risks, ask yourself: if not us, *then who?*

b. <u>Beware the seduction of novelty.</u> We are often engaged in exploring and evaluating technologies which have not been employed before: that which is "new" necessarily draws our attention. Spin testing, on the other hand, is nearly as old as human flight itself. Herein lies a paradox: with less than 2% of SETP papers addressing spin testing in the past 10 years, it's a safe bet that our program would feel like a very "new" kind of testing for the vast majority of active testers today. Based on personal experience, we can assure you: the fact that spin testing has been around for over 100 years will be of little comfort the moment you initiate your first elevated-risk spin test point. Like frequency-of-use, we submit the importance of a test discipline should not be assessed by how "new" it may be.

c. <u>Realize there are things worse than confrontation.</u> Anyone of us who have had to bury a fellow tester probably appreciates this best. Preventing disaster requires you to speak up when you encounter a hazard that has not been adequately dealt with. It's critical to have your facts correct beforehand, and worth the time to find relevant, credible third-party sources to support your position. If the engineering facts back you, persist: respectfully, tactfully – yet unapologetically – until the matter is satisfactorily resolved. No, you may not always make friends in the process . . . but understand that your silence under such circumstances <u>*absolutely counts*</u> as a 'go' vote: if it didn't, you probably wouldn't be on the test team. Are you prepared to live with the consequences?

d. <u>Publish.</u> Widely-understood test hazards are more difficult to dismiss. Spin testing is notoriously hazardous, yet perhaps not well understood, given the small number of us who have done it. This is no small irony: the dismissiveness this lack of understanding invites can stand as an obstacle to being published . . . thereby helping multiply the dismissiveness. To the credit of the SETP Publications Committee, we offer this paper into evidence: persistence *can* overcome a harmful dynamic that might otherwise prove self-sustaining. It should be clear that our test team owes a debt of gratitude to those who came before us – and who had the foresight to allow us to preemptively learn what they discovered. As you weigh the merit of following in their footsteps, also consider this: to the extent that your efforts to publish life-saving lessons-learned encourage your peers to do likewise, the life you ultimately save may be your own.

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